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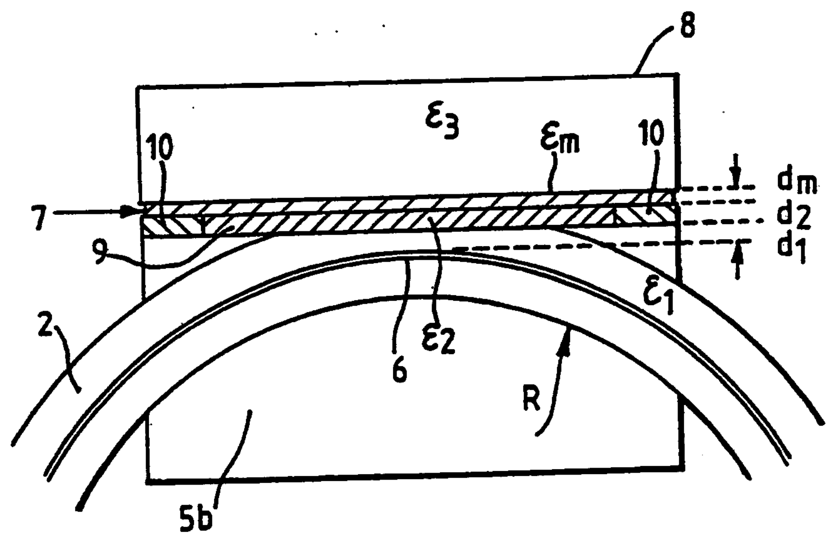
(54) Title: OPTICAL FIBRE COMPONENTS



(57) Abstract

The application describes a number of optical fibre components based on surface plasmon wave generation, wherein an arc of optical fibre (1) is set in a substrate (5) with its core (3) at or near the substrate surface to provide incident light, and wherein a film (7) of material having a negative real part dielectric constant is provided at the substrate surface. The components can act as polarizers, modulators, sensors and polarizing couplers.

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OPTICAL FIBRE COMPONENTS

This invention relates to a set of optical fibre components based upon surface plasmon wave (SPW) generation across a thin preferably metal film with negative real part dielectric constant (active medium) in close proximity to the fibre core. Generation of the SPW relies on evanescent field coupling from an incident optical beam. To achieve this the phase velocity of the optical wave must be reduced to match that of the SPW.

Conventionally, in bulk optics the evanescent field is created by total internal reflection at the base of a high refractive index prism. The thin active (metal) film is either brought into close proximity with (Otto configuration) or deposited directly onto the base of the prism (Kretchman configuration). The input beam angle of incidence can then be adjusted to vary the component of the incident phase velocity parallel to the interface. At a particular angle the matching condition is realised and the coupling of energy to the SPW indicated by the reduction in reflected power. This method of plasmon generation has been used by many researchers to study the propagation of SPWs.

Several interesting properties are exhibited. The SPW propagates along the metal surface with a penetration depth of several nanometers in both sides. The wave is highly polarized coupling only p-polarized (TM-like) light. The form of the SPW depends upon the thickness of the metal film and the refractive index of the adjoining materials. In general, a thin metal film with negative real dielectric constant and thickness 10-40nm bounded by two dieletric media with real positive dieletric constants supports four distinct SPW modes. Two of them are bound (symmetric and antisymmetric) and the other two leaky into the surrounding dielectrics. The excitation of a particular mode depends on the relative dielectric constants of the dielectrics, the thickness of the metal and the wavelength of the light.

There has also been described a metal-clad fibre-optic cutoff polarizer in Optics letters/Vol. II, No. 6/June 1986/page 386 (Feth and Chang).

According to the invention there is provided an optical fibre component based on surface plasmon wave generation, wherein an arc of optical fibre is set in a substrate with its core at or near the substrate surface to provide incident light, and wherein a film of material having a negative real part dieletric constant is provided at the substrate surface.

Preferred embodiments of the invention are described below, by example only, with reference to the accompanying drawings, wherein:

Figs 1 to 3 are schematic sectional views showing techniques for generating SPWs;

Figs 2 to 8 are schematic sectional views showing components according to the present invention;

Figs. 9 and 10 show transmission/refractive index results.

To induce surface plasmon wave (SPW) coupling in an optical fibre configuration the cladding 2 must be partially removed from the fibre 1 to give access to the evanescent field. The technique used in this application is to epoxy the optical fibre 1 in a slot 4 within a dielectric substrate block 5, for example a glass block. The slot is on a radius R such that the fibre is closer to the substrate surface at the centre of the slot. The surface of the substrate is lapped and then polished until the evanescent field of the guided wave extends beyond the block surface. This condition occurs when the surface is within microns (for example one micron) of the core 3. The precise distance from the core is variable and depends upon the type of device; in some components the fibre may be polished into the core. Figure 1 shows a schematic view of the polished

fibre in the substrate block, the fibre being on a radius of 25cm, for example.

To excite SPWs two configurations shown in Figures 2 and 3 are used. Figure 2 shows the device with a metal film 7 deposited directly on the glass block and a different material 8 above the metal, here termed a "superstrate". The metal can be Aluminium or Silver, for example, deposited on the substrate by evaporation or sputtering to a thickness of 10nm-25nm. The "superstrate" material can take various forms as indicated later and may consist of several layers with varying magneto-optic and electro-optic properties and thicknesses. Figure 3 shows the device with a buffer material used to control the coupling conditions through the device. Different forms of the SPW can be generated dependent upon the active film thickness and the interfacing dielectrics. For thick metals (>40nm) highly attenuated TM-like waves are produced at the metal interfaces.

As mentioned above, an arrangement vaguely similar to that shown in Fig. 2 has previously been disclosed in the paper in "Optics Letters", though there the fibre is polished into the core.

The configurations shown in Figures 2 and 3 can both be used as high performance polarizers when SPWs have been excited

across the thin active film and the surrounding dieletrics.

In Figure 2, a thin metal film ($10nm<d_m<40nm$) of negative real part dielectric permittivity $\mathcal{E}_m$ has been deposited straight on top of the polished surface of the substrate 5 and covered by another layer 8 of permittivity $\mathcal{E}_3$. The "superstrate" layer may be of glass with an appropriate refractive index, for example in the range 1.4 - 1.5, or a dielectric material with refractive index lower than 1.4, for example M_gS_2 with refractive index 1.38. The permittivity of the fibre is $\mathcal{E}_1$. The depth of the polishing is characterised by the thickness of the remaining cladding d_1, and the radius R of the bent fibre.

The excitation of a particular SPW mode (leaky/bound) is determined by the specific values of the parameters $\mathcal{E}_1$, d_1, R; $\mathcal{E}_m$, d_m, and $\mathcal{E}_3$. In case the polishing depth (d_1) is such that both polarizations (TE/TM) are well guided before the deposition of the thin active film, the remaining undetermined parameters are adjusted appropriately so that either SPW mode is excited. Only the TM mode is coupled while the TE mode is unaffected by the choice of those parameters and remains well guided.

Coupling into leaky SPW mode causes the incident TM polarization to leak out into the superstrate, while it

propagates in the interaction area. The longer the interaction length, i.e. the larger the radius of the curvature R, the better the polarization extinction ratio of the component.

Excitation of a bound SPW causes the incident TM polarization to propagate along the thin metal film suffering attenuation due to Ohmic losses. The attentuation of the bound SPW mode is of a different nature from and appreciably lower than the attenuation experienced by the leaky SPW mode, and results in long propagation distances. Consequently, and undesirably, the interaction length may be overshot and part of the unextinguished TM-SPW mode recoupled into the fibre deteriorating the performance of the polarizer.

In Figure 3 an alternative configuration is shown where SPWs can be excited. The thin active film 7 ($\mathcal{E}_m, d_m$) is now deposited onto the polished surface of a separate dielectric block ($\mathcal{E}_3$), the "superstrate", and brought into close proximity with the polished surface of the substrate 5b. A dielectric $\mathcal{E}_2$ with thickness d_2 is placed in between the metal and the polished surface as a buffer layer 9. The buffer layer may be oil, the thickness of the oil layer being determined by spacers 10. Once all the other parameters are fixed, the thickness (d_2) and the dielectric

constant ($\mathcal{E}_2$) of the buffer layer are used to selectively excite leaky or bound SPW modes. For effective coupling to SPWs $10nm<d_m<40nm$ and $100nm<d_2<700nm$.

For $\mathcal{E}_2<\mathcal{E}_3$, the incident TM polarization couples to a leaky SPW mode which is radiated into the superstrate. The TE mode is propagated unaffected. Again, large radii of curvature ($30cm<R<100cm$) result in long interaction length and polarizer with better performance. In this regime the TE polarization is transmitted and the TM extinguished.

For $\mathcal{E}_2>\mathcal{E}_3$, the incident TM polarization couples to a bound SPW mode which propagates along the thin active film with very low attenuation. After passing the centre point 6 the SPW mode recouples into the fibre due to the reciprocity principle. To minimise the Ohmic losses experienced by the bound SPW mode the interaction length should be very short, i.e. the radius of curvature small ($15cm<R<30cm$). Since $\mathcal{E}_2>\mathcal{E}_3>1$, the buffer layer forms a waveguide which couples the incident TE mode. By choosing d_2 to be different from $m(\lambda/2)$ this mode is cut off and does not recouple into the fibre (λ is a wavelength of the incident wave and m integer). In this regime the TE polarization is extinguished while the TM is transmitted with very low attentuation.

Variation of the thickness of the buffer layer is possible,

as discussed below, to provide for intensity modulation. The generation of the SPW depends very critically upon the precise matching conditions being met, producing a resonance type response about the matching condition. Variations in the values in refractive index and dimensions of the superstrate, substrate and buffer layers produce modification of the optical transmission properties of the device. This effect is used to produce intensity modulation in a variety of ways.

The first shown in Figure 4 is a modified version of the polarizer of Figure 3 and functions as an intensity modulator of the transmitted TM-polarization. Its operations relies upon the variation of the buffer-layer thickness so that the SPW resonance is perturbed and the transmission modulated.

The spacers in this embodiment are resilient so that they can apply a restoring force. The buffer-layer thickness is varied by means of a PZT transducer poled in its thickness mode which is placed on top of the superstrate. The whole device is held in a supporting structure 12. By applying an alternating voltage across the PZT plate an alternating displacement is produced which is transferred to the buffer-layer and modifies its thickness d_2. Variations in the thickness produce an intensity modulation of the transmitted

polarization. The buffer layer thickness can also be modulated by any mechanical means, instead of the PZT transducer.

Variation of the buffer layer thickness gives a mechanically variable attenuation to the light propagating in the TM-polarization.

Both configurations shown in Figures 2 and 3 can be used as intensity modulators when the "passive" "superstrate" is replaced by an "active" one. Crystalline electrooptic materials (for example KDP) and known magnetooptic materials are considered to be "active" in this case. When the crystal orientation is such that TE-TM polarization coupling is allowed, the component operates as an intensity modulator of the transmitted polarization upon the application of an alternating electric or magnetic field respectively.

In Figure 3, instead of the superstrate being replaced, the dielectric buffer layer 9 only can be replaced by a grown thin electroopic or magnetooptic crystal with the same orientation as above and similar results are achieved.

The application of a.c. or d.c. electric fields or magnetic fields to provide for frequency shifting and phase modulation will now be discussed.

Under the correct conditions the optical wave will couple to the surface plasmon, propagate along the metal film and then recouple to the optical fibre. Whilst in the metal film the properties of the wave can be modified. The conditions to generate long range SPW (LRSPW) are created by varying the refractive index of the layers above and below the metal film. The conditions are created such that the guided optical wave couples into the SPW before reaching the centre of the device and the SPW couples back to a propagating optical wave at the symmetrical position past the centre due to reciprocity.

Applying a voltage across the metal film produces a drift of the electrons which support the SPW. The drift velocity is proportional to the applied voltage through Ohms law.

This drift produces a Doppler frequency shift of the SPW which when recoupled to the optical fibre mode is transferred to the optical wave. This gives a single sideband frequency shift of the light proportional to an applied d.c. voltage. Similarly an a.c. applied to the metal film produces a phase modulation of the propagating plasmon wave. This form of modulation can be taken to high frequencies i.e. into the GHz region.

An alternative approach is to replace the metal with a semiconductor material (e.g. doped silicon) and apply a voltage to this modifying the carrier density and effecting the plasmon propagation to produce phase modulation and frequency shifting.

Another approach is to use the configurations shown in Figures 2 and 3 with the "passive" dielectric superstrate (or the buffer layer 9 in Figure 3) replaced with an "active" electrooptic or magnetooptic crystalline material. The crystal is now oriented so that TM-TM (or TE-TE) polarization coupling is allowed. Upon application of an alternating electric or magnetic field respectively the described components result in phase modulation of the propagating polarization.

The properties of the surface plasmon are dependent upon the refractive index of the material above the metal. Variations of this refractive index produce a very sensitive sensor.

The material adjacent to the metal film can be chosen to have a refractive index which is sensitive to a particular measurand. For example, chemical sensing, biosensing, temperature sensing etc. Figure 5 shows the configuration. In this case either A or B can be the sensitive medium, the

refractive index of the other medium (B or A) being known. The light of the appropriate polarization will be coupled to the SPW under the correct conditions. This matching is a very sharp function of the refractive indices of both materials A and B, and by monitoring the level of the output optical power (by conventional means) the condition of the measurand (indicated by the arrows) can be assessed.

Electric fields may be detected by using material with a refractive index dependent upon the field intensity. Alternatively, a direct detection of the electric field can be made by detecting any induced frequency or phase shift on the LRSPW. Magnetic field detection may also be made by the same techniques. These devices give directional information of the electric and magnetic fields.

Some of the devices described so far in this application rely upon the surface plasmon recoupling to the same guide. This is not essential and certain devices can be constructed which couple the plasmon wave to a second fibre.

Figure 6 shows the form of such a switching component. It is essentially two devices placed together. A material 14 can be placed between them with variable refractive index (sensitive to applied field or a measurand in sensing applications). Variation of the material will affect the

coupling from one fibre to the other. The intermediary material can be, a dielectric, a non-linear material (e.g. Kerr effect material), liquid crystal or semiconductor. The device of Figure 6 may have only a single metal layer and the fibre radius of curvature may be different for each block.

In the case that the intermediary material exhibits a Kerr-type non-linearity and has an ordinary refractive index higher than that of the buffer layer 9 the switching can be controlled by light of different wavelength λ_2. In such an arrangement the intermediary layer 14 forms a separate waveguide where light of wavelength λ_2 and variable intensity can propagate and change the intensity dependent refractive index. Therefore, switching of the desired wavelength λ_1, can be achieved by controlling the intensity of wavelength λ_2.

Figures 7 and 8 show two alternative configurations of a polarizing coupler. The SPW effect is used for the polarization selectivity. Polarization-selective couplers are fibre-optic components which transfer efficiently one polarization from an input fibre to a second one and transmit the orthogonal polarization unaffected. Such a device is useful in wavelength multiplexing, polarization diversity detection schemes and fibre Raman amplifiers.

Known configurations consist of two single-mode fibres coupled together utilizing either fusion or polishing techniques. Their function is based upon the differential beating of the symmetric and antisymmetric eigenmode for each of the two orthogonal polarizations present in the coupling region. The degeneracy between the propagation constants of the two orthogonal polarizations is broken either by exploiting the form birefringence in the interaction length or by using high-birefrigence fibres polished in perpendicular directions in different depths.

Described herein is a novel configuration of a polarizing beam splitter of polished type. The polarization splitting is achieved by making use of the polarization sensitive surface plasmon-wave resonance in the coupling region. As discussed above, surface plasmons are TM electromagnetic modes in the optical regime supported by a dielectric-metal interface when the dielectric permittivity of the metal (active medium) is negative. When the active medium takes the form of a thin metal film the surface plasmons of the two separate interfaces combine together to give four different eigen-modes.

In all-fibre optical systems polishing the fibre is an ideal method of accessing the evanescent field of the propagating beam with very low insertion loss. In Figs 7 and 8, two

pieces of high-birefringence fibres, York Technology, single-moded at 633 nm have been aligned with their slow axes perpendicular to the polished surface to within 1o accuracy. Arcs of 25cm radius were engraved onto the glass substrates, and the fibres firmly bonded into them. The blocks were then polished to a few microns from the core. A thin Aluminium film (25nm) was deposited onto the polished block I.

To evaluate the transmission characteristics and the efficiency of coupling to plasmon modes, the polished glass blocks were tested separately for two wavelengths, namely 633 nm and 850 nm.

Drops of liquid of various refractive indices were placed on top of the polished surface of one block. A thin Al film (25 nm) was deposited on a separate glass block and brought to close proximity to the polished surface. The refractive index liquid was forming a buffer layer whose thickness was optimised each time for optimum results by applying pressure. The results are shown in Figure 9. Curve 1 corresponds to the transmission of the polished block when a drop of oil, taken as a semi-infinite medium, was placed on top. Curve 2 corresponds to the transmission with the metal film bought in close proximity to be polished surface and optimum buffer layer thickness. Figures 9 (a), (b)

correspond to the case where light with TM-like polarization and wavelength 633 nm and 850 nm was launched respectively. The other polished block was subjected to a similar test. Drops of liquids of various refractive indices, considered as a semi-infinite media, were placed on top of the deposited Al film in the polished area and the results aer shown in Figure 10. Figures 10 (a) and (b) correspond again to TM-like polarization and wavelengths 633 nm and 850 nm respectively.

The minima in the transmission of both blocks (Fig. 9,10) correspond to coupling of the fundamental fibre mode to a leaky mode of the composite structure in the interaction area. The light was leaking into the superstrate having the characteristic crescent form at an angle determined by the propagation constant of the leaky mode.

In the configuration of Figure 7, the polished block 5 is placed on top of a similar block with a deposited thin active film ($\mathcal{E}_m$,d_m). A liquid buffer layer ($\mathcal{E}_2$,d_2) is placed between the counterfacing surfaces. The refractive index $\mathcal{E}_2$ (for example 1.458) should be less than the effective refractive index of the fibre ($\mathcal{E}_1$) and the parameters (d_2,d_m) are adjusted so that the SPW resonance occurs. TM-polarization launched into port 1 (3) couples to SPW across the thin active film and cross-couples into port

4 (2). TE-polarization launched into port 1 is transmitted unaffected to port 2 no matter what the value of $_2$ is. The condition $\varepsilon_2 < \varepsilon_1$ should be met in order that TE-polarization launched into port 3 to be transmitted unaffected to port 4 as well.

When metal films with thickness between 17 and 25 nm are used, dielectric materials with $\varepsilon_2 > \varepsilon_1$ can be used, resulting in a high performance polarizing beam splitter.

With light of both polarizations being launched into port 3, the polarization selectivity of the TM-like polarization was measured to be 12dB and 20dB at 633 nm and 850nm respectively. The TE-like polarization was transmitted through without coupling to port 4. The insertion loss was less than 1dB at 633 nm and about 4dB at 850nm.

An alternative approach is shown in Figure 8. Thin active films (ε_m,d_m) are deposited on both polished substrate blocks and a dielectric buffer layer (ε_2,d_2) placed in between. TM-polarization launched into port 1 (3) couples into SPW supported by the composite structure ε_1-ε_m-ε_2-ε_m-ε_1 and recouples into port 4 (2). The TE-polarization is transmitted unaffected.

To summarize, in both configurations shown in Figures 7 and

8, light launched into port 1 (3) transmits its TE-polarization component to port 2 (4) and cross-couples the orthogonal TM-polarization into port 4 (2).

The fibre used herein is single-mode and access to the evanescent field is gained through mechanically removing the cladding. The fibre may be standard communications optical fibre. The above devices can be constructed with polarization maintaining fibre of various configurations. Also access to the evanescent field might be obtained by tapering, etching or manufacturing the fibre with the core close to the surface. Multimode fibres can also be used in the devices described above.

CLAIMS:

1. An optical fibre component based on surface plasmon wave generation, wherein an arc of optical fibre is set in a substrate with its core at or near the substrate surface to provide incident light, and wherein a film of material having a negative real part dielectric constant is provided at the substrate surface.

2. A component according to claim 1, wherein a buffer layer of dielectric material is provided between the substrate and the film.

3. A component according to claim 1 or 2 which forms a polarizer.

4. A component according to claim 2, comprising means to vary the thickness of the buffer layer, thereby providing intensity modulation.

5. A component according to claim 2, wherein the buffer material has a variable refractive index, thereby providing intensity modulation.

6. A component according to claim 1 or 2, comprising a superstrate atop the said film, the refractive index of the superstrate being variable.

7. A component according to claim 1 or 2, comprising means to apply a d.c. or a.c. voltage across the film, thereby providing frequency shifts or phase modulation.

8. A component according to claim 1, wherein a material is provided adjacent the said film whose refractive index varies according to a given measurand, the component further comprising means to detect charges in output power, frequency or phase, the component thereby acting as a sensing device for that measurand.

9. A switching device comprising a pair of components according to claim 1 or 2, a material of variable refractive index being provided between the films of the two components, whereby coupling between the fibres can be controlled.

10. A polarizing coupler comprising a component according to claim 1 and a second substrate with an arc of optical fibre set therein, a dielectric buffer layer being provided between the film of the component and the surface of the

second substrate, and the refractive index of the buffer layer being less than the effective refractive index of the fibre in the case of thin films or greater in the case of thicker films.

11. A coupler according to claim 10, wherein a film of material having a negative real part dielectric constant is also provided on the surface of the second substrate.

12. A component, device or coupler according to any preceding claim wherein the said film is a metal or semiconductor material.

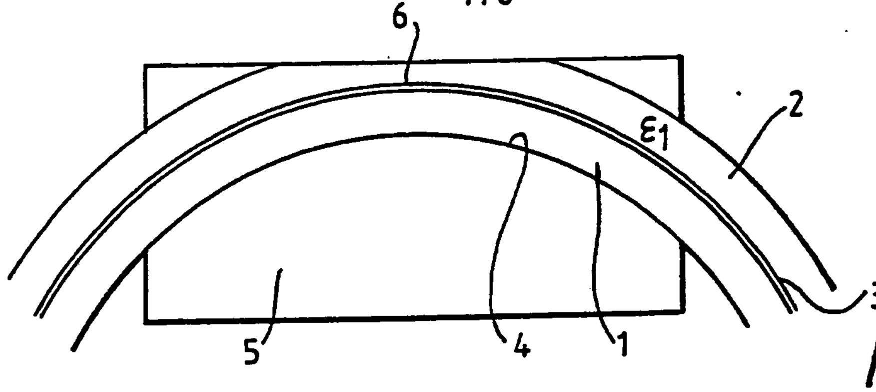

Fig.1.

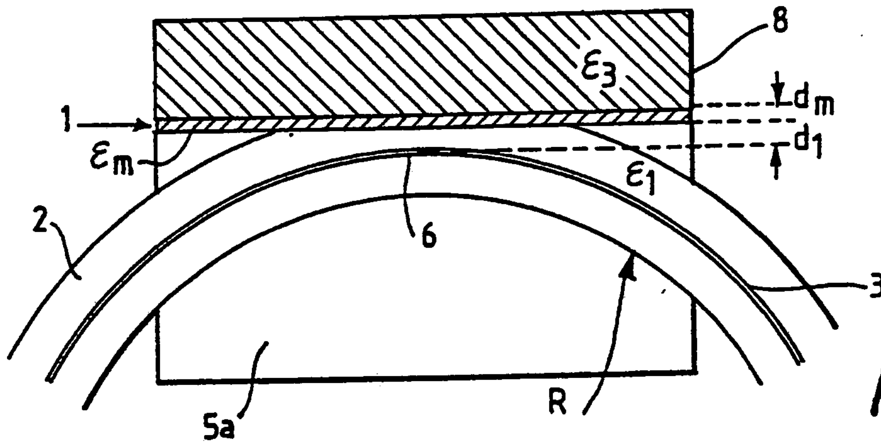

Fig.2.

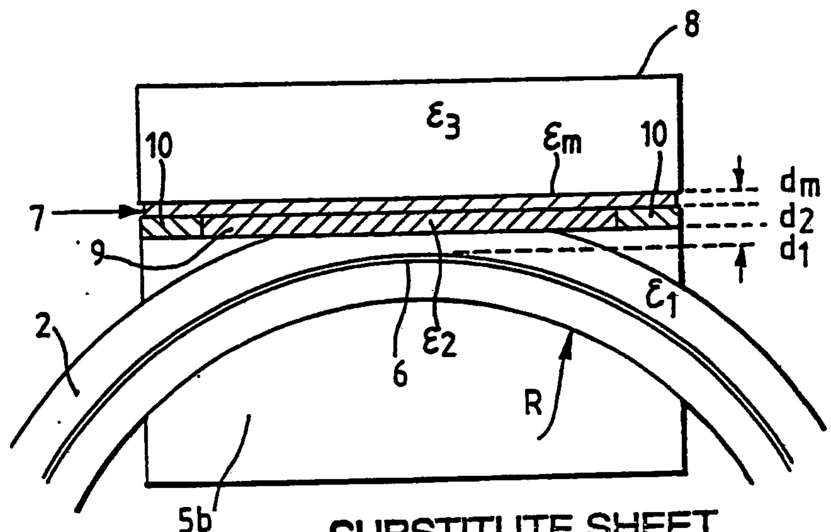

Fig.3.

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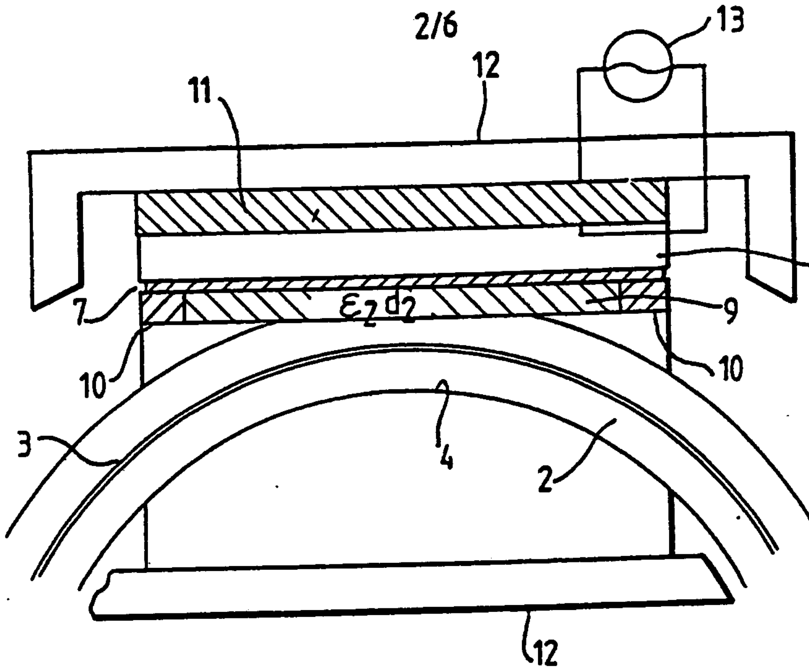
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$\varepsilon_2 d_2$
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Fig.4.

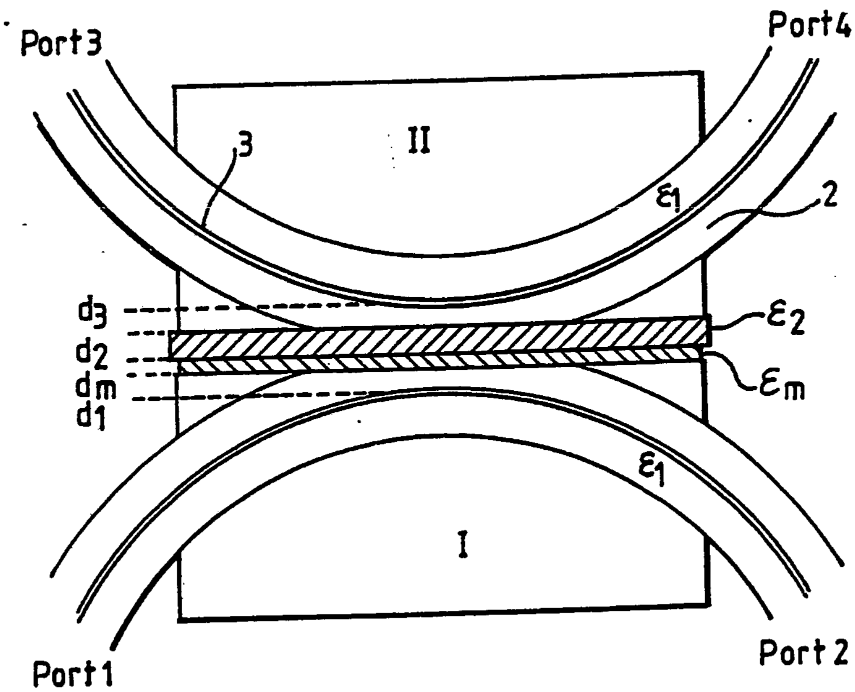
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Fig.7.

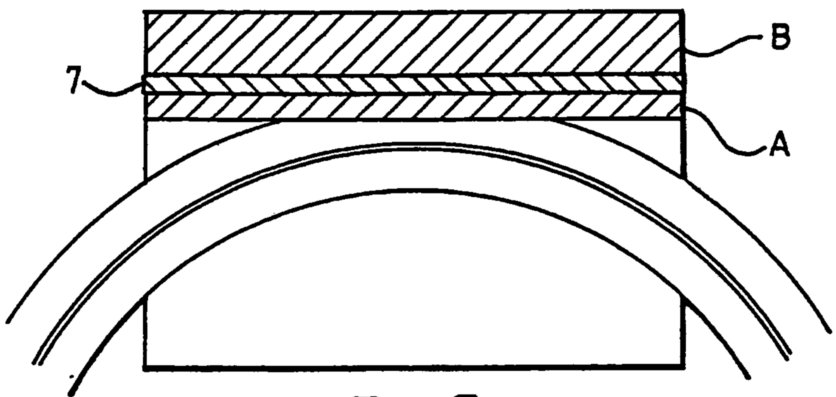


Fig.5.

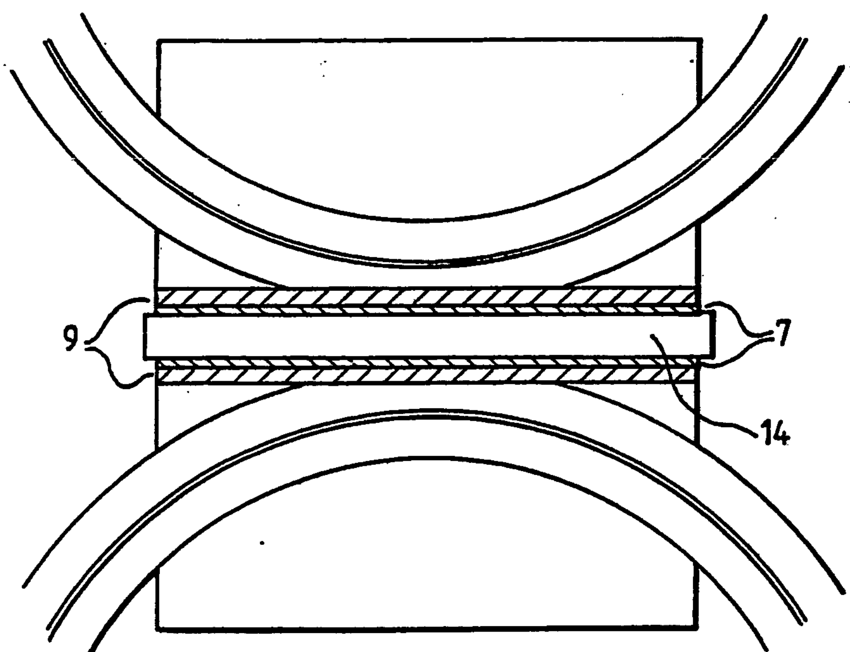
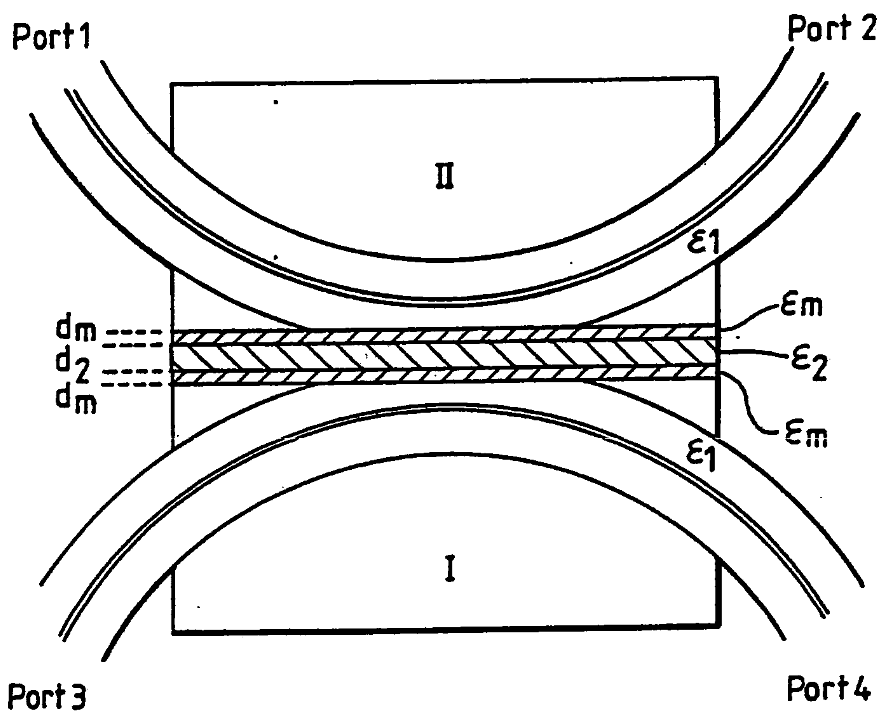


Fig.6.


Port 1
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Port 4

Fig.8.

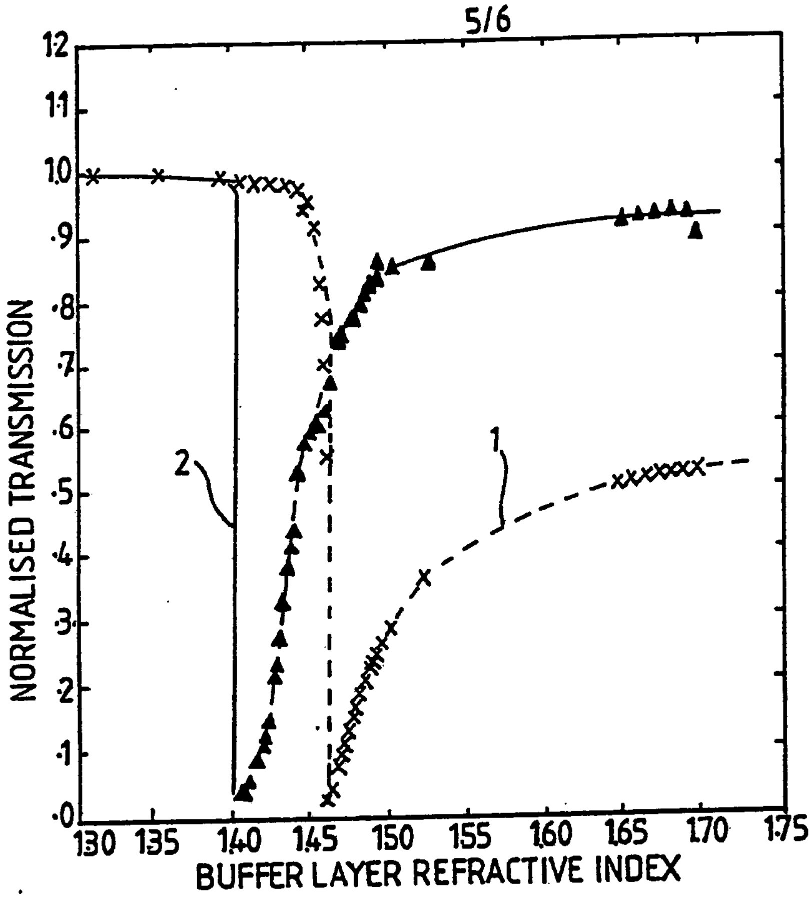
NORMALISED TRANSMISSION
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Fig.9a.

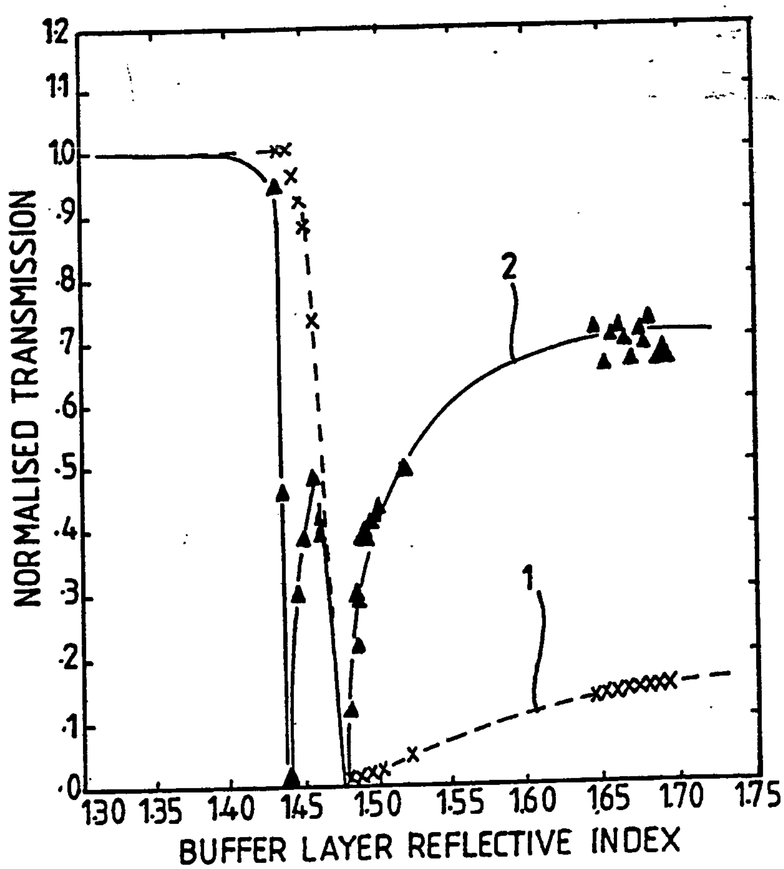
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Fig. 9b.

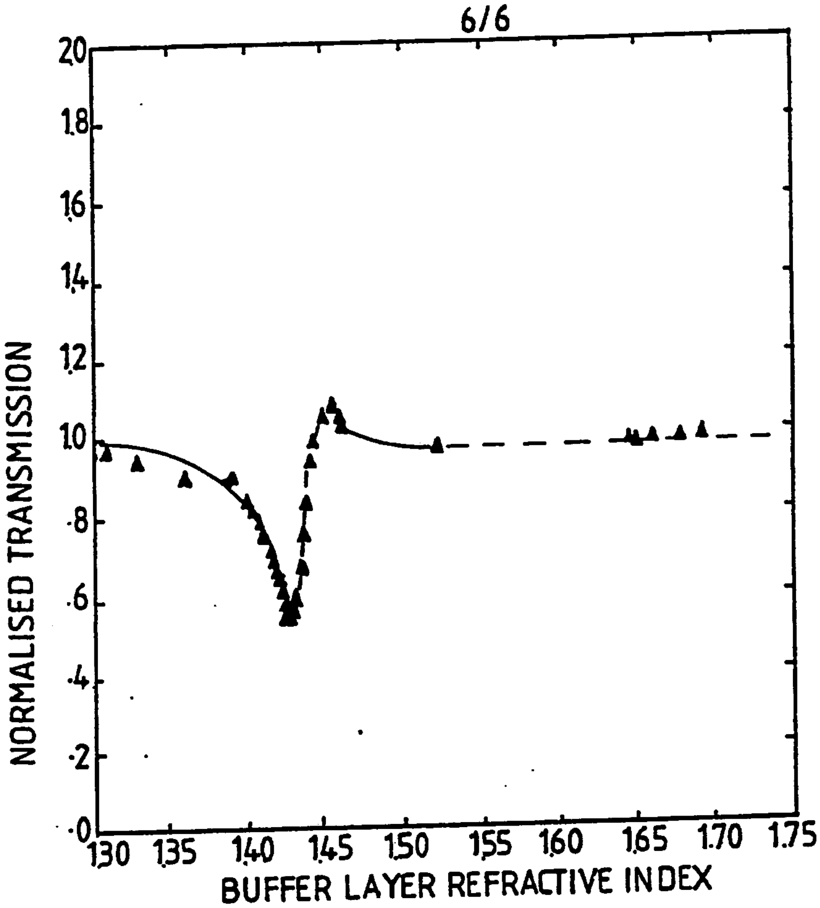

Fig.10a.

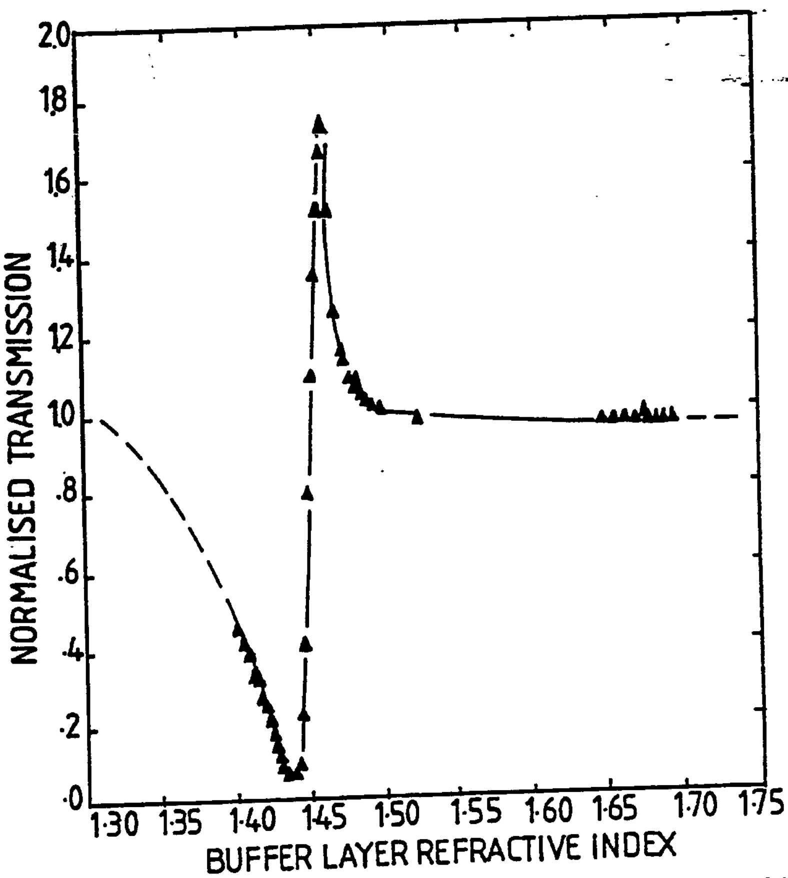

Fig.10b.

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 88/00623

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC[4] G 02 B 6/26, G 02 B 6/14, G 02 F 1/01

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
IPC[4]	G 02 B, G 02 F, H 01 L

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X Y	EP, A2, 0212773 (LITTON SYSTEMS INC.) 4 March 1987, see abstract and claims	1,3,12 2,9,10,11
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Y	APPLIED OPTICS; Vol. 22, No. 23, 1 December 1983, Fiber Circular Polarizer. T. Hosaka, K. Okamoto, and T. Edahiro see fig. 5 page 3852	2

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

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IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
29th September 1988	17 NOV 1988
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	P.C.G. VAN DER PUTTEN

Form PCT/ISA/210 (second sheet) (January 1985)

International Application No. PCT/GB 88/00623

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
Y A	US, A1, 4387954 (BEASLEY) 14 June 1983 see abstract fig, 4, column 3, lines 40-42 column 1 lines 34-37 --	9,10,11 8
Y A	WO 87/04261 BRITTISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY) 16 July 1987 see page 3, 2nd paragraph, page 9, 1st paragraph --	9,10,11 7
A	US, A1, 4386822 (BERGH) 7 June 1983 whole document --	
A	US, A1, 4493528 (SHAW et al.) 15 January 1985 whole document --	
A	US, A1, 4583818 (CHEN et al.) 22 April 1986 see abstract --	4, 5
A	US, A1, 4598728 (DYOTT et al.) 20 May 1986 see abstract lines 16-20 --	6
A	US, A1, 4666235 (PAVLATH) 19 May 1987 whole document --	
A	EP, A1, 0178045 (LITTON SYSTEMS INC.) 16 April 1986 see abstract --	7
A	WO 87/04260 (BRITTISH TELECOMMUNICATIONS PUBLIC LIMITED COMPANY) 16 July 1987 whole document --	
A	DE, A1, 3305104 LICENTIA PATENT-VERWALTUNGS GmbH 16 August 1984 whole document --	
T	ENCYCLOPEDIA OF PHYSICS Dielectric properties, Nicholas Bottka, see page 202, 3rd paragraph, definition of negative real part Dielectric constant and plasma oscillations (the plasmon) ------------	

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
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US,A1 4359260	16/11/82	None	
US,A1 4387954	14/06/83	None	
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